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COMPARISON BETWEEN THE DIELECTRIC DATA DERIVED FROM CURRENT AND VOLTAGE TIME DOMAIN MEASUREMENTS

Vladimír Ďurman — Martin Wiesner
Jaroslav Lelák — Ondrej Olach *

In this paper a review is given of different computing procedures for evaluation of the absorption current and recovery voltage measurements in dielectric systems. A new method based on the recovery voltage measurement is also presented and compared with some selected methods used in this field. All selected measuring and computing procedures were applied to the dielectric data measured on a simple circuit consisting of discrete components as well as on real dielectric of PVC cables. It was shown that the new method based on the Fourier transform of recovery voltage data is much faster and less complicated than the method of modelling the transient by means of an equivalent circuit. Possible sources of errors arising from application of the method are discussed in conclusion of the paper.

K e y w o r d s: dielectrics, dielectric response, insulation systems

1 THE DIELECTRIC CHARACTERISTICS IN THE TIME DOMAIN AND FREQUENCY DOMAIN

Dynamic properties of a linear system are usually represented by three characteristics:

a) The impulse response $h(t)$ — response of the system resulting from unit impulse $\delta(t)$.
b) The step response $g(t)$ —- response of the system resulting from the unit-step function $u(t)$.
c) The transfer function $H(p)$, $H(\omega)$ — the ratio of the Laplace (or the Fourier) transform of the output signal and the transform of the input signal.

In the theory of dielectrics the electric field $E(t)$ is considered as the system input signal and the polarisation $P(t)$ as the system output signal. The system response to an arbitrary electric field E is

$$P(t) = \varepsilon_0 \int_0^t h(t-\lambda)E(\lambda)\mathrm{d}\lambda\,, \tag{1}$$

where ε_0 is permittivity of free space.

In experiments the polarisation $P(t)$ is not measured directly. A commonly used technique in this field is the measurement of the so-called relaxation (absorption) current after a step voltage application. The current density can be evaluated from Maxwell equations. Let γ_0 denote the dielectric conductivity. After application of a step electric field E_0 at time $t=0$ the current density $i(t)$ is given by

$$\begin{aligned} i(t) &= \gamma_0 E_0 + \varepsilon_0 \frac{\mathrm{d}E(t)}{\mathrm{d}t} + \varepsilon_0 \frac{\mathrm{d}}{\mathrm{d}t}\int_0^t h(\lambda)\mathrm{d}\lambda \\ &= \gamma_0 E_0 + \varepsilon_0 E_0 \delta(t) + \varepsilon_0 E_0 h(t)\,. \end{aligned} \tag{2}$$

Dividing (2) by E_0 we get a formal expression for the time dependence of conductivity after application of a step electric field

$$\gamma(t) = \gamma_0 + \varepsilon_0\delta(t) + \gamma_a(t)\,. \tag{3}$$

The conductivity step response is given by the sum of the steady-state (dc) conductivity, the unit impulse and the absorption conductivity characterising the dielectric relaxation process. The absorption conductivity is a part of *the current step response* and it equals (after dividing by ε_0) to *the polarisation impulse response*

$$\gamma_a(t) = \varepsilon_0 h(t)\,. \tag{4}$$

When changing from the time domain to the frequency domain, the relationship between the transfer function and the impulse response is preferably used. As the Fourier transform of the unit impulse is 1, the transfer function can be computed directly as the Fourier transform of the impulse response

$$\frac{P^*(\omega)}{\varepsilon_0 E^*(\omega)} = \int_0^\infty h(t)\exp(-j\omega t)\mathrm{d}t\,, \tag{5}$$

where sign * denotes complex variables.

* Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Ilkovičova 3, 812 19 Bratislava, Slovakia

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The term on the right side of (5) is the complex susceptibility χ^*. By using the relationship between the complex susceptibility and the complex permittivity ($\varepsilon^* = 1 + \chi^*$) and supposing that the contribution of the fast polarisations to the permittivity is ε_∞, we have

$$\varepsilon^*(\omega) = \varepsilon' - j\varepsilon'' = \varepsilon_\infty + \frac{1}{\varepsilon_0}\int_0^\infty \gamma_a(t)\exp(-j\omega t)\mathrm{d}t\,. \quad (6)$$

Expression (6) is the basic relationship used for conversion of the dielectric data from the time domain into the frequency domain.

2 CALCULATION OF THE COMPLEX PERMITTIVITY FROM THE ABSORPTION CONDUCTIVITY

2.1 Discrete Fourier transform

In practice the measured data are available in the form of discrete values of time and conductivity. Taking this fact into account the former continuous-time Fourier transform must be replaced by discrete Fourier transform (DFT). For DFT the next expressions are valid

$$\begin{aligned}\varepsilon'(m\Delta f) &= \frac{\Delta t}{\varepsilon_0}\sum_{k=0}^{N-1}\gamma_a(k\Delta t)\cos\big(2\pi\frac{mk}{N}\big)\,,\\ \varepsilon''(m\Delta f) &= \frac{\Delta t}{\varepsilon_0}\sum_{k=0}^{N}\gamma_a(k\Delta t)\sin\big(2\pi\frac{mk}{N}\big)\,,\end{aligned} \quad (7)$$

where Δt is a sampling interval, N is a number of samples and $\gamma_a(k\Delta t)$ are measured values ($k = 0, 1, \ldots, N-1$). The discrete Fourier transform provides the frequency dependence of the real and imaginary parts of the complex permittivity at points which are multiples (m) of the base $\Delta f = (N\cdot\Delta t)^{-1}$ for $m = 0, 1, \ldots, m_{\max}$. DFT is valid only below the Nyquist frequency $f_N = (2\cdot\Delta t)^{-1}$. It should be mentioned that DFT has a modification known as a fast Fourier transform. In spite of its advantages, the method is not frequently used. In the field of dielectric spectroscopy some methods are preferred, which attempt to reduce the number of samples needed for transformation [1]. The methods are based on the assumption that conductivity can be approximated over a wide range of values by an empirical function

$$\gamma_a(t) = \gamma_1 t^{-n}\,, \quad (8)$$

where n is a parameter and γ_1 is the value of conductivity at time $t = 1$. In this case the integral of Fourier transform can be easily evaluated for various n by using Gamma function Γ

$$\begin{aligned}\varepsilon'(\omega) &= \frac{\gamma_1}{\omega^{1-n}\varepsilon_0}\Gamma(1-n)\sin\frac{n\pi}{2}\,, \quad 0 < n < 1\,,\\ \varepsilon''(\omega) &= \frac{\gamma_1}{\omega^{1-n}\varepsilon_0}\Gamma(1-n)\cos\frac{n\pi}{2}\,, \quad 0 < n < 2\,.\end{aligned} \quad (9)$$

If the function $\varepsilon''(\omega)$ is treated only for points $\omega t = 1$ then one can write

$$\varepsilon''(\omega) = \frac{\gamma_a(t)t}{\varepsilon_0}\Gamma(1-n)\cos\frac{n\pi}{2}\,, \quad 0 < n < 2\,. \quad (10)$$

2.2 The Hamon approximation

The method is based on equation (10). It is supposed that the loss factor can be expressed by $\varepsilon''(\omega) = \frac{\gamma_a(t)}{\omega\varepsilon_0}$ and the relationship between time and frequency has a form $f = \frac{y(n)}{t}$. For the function $y(n)$ Hamon derived

$$y(n) = \frac{1}{2\pi}\Big[\Gamma(1-n)\cos\frac{n\pi}{2}\Big]^{-\frac{1}{n}}. \quad (11)$$

He also showed that $y(n)$ does not depend on n for $0.3 < n < 1.2$ and equals to 0.1 with accuracy of 3 % [2]. Considering these results, we have

$$\begin{aligned}\varepsilon''(\omega) = \frac{\gamma_a(t)}{\omega\varepsilon_0} &= \frac{\gamma_a(t)}{2\pi f\varepsilon_0} = \frac{\gamma_a(t)t}{2\pi y\varepsilon_0}\\ &= \frac{\gamma_a(t)t}{0.2\pi\varepsilon_0} = 1.8\times 10^{11}\gamma_a(t)t\,. \end{aligned} \quad (12)$$

In a similar way Adamec derived a frequency dependence for $\varepsilon'(\omega)$ [3]

$$\begin{aligned}\varepsilon'(\omega) &= \frac{\gamma_1 t^{1-n}}{\varepsilon_0(1-n)}\,, \quad 0 < n < 1\,,\\ f &= \frac{x(n)}{t}\,, \quad x(n) = 0.035 + 0.055n\,.\end{aligned} \quad (13)$$

2.3 The Hyde approximation

Hyde [4] developed a method in which a specific charge q is used instead of conductivity. Specific charge is defined as a charge on an unit area with unit electric field, divided by ε_0. He supposed that the time dependence of the specific charge after application of a step electric field is linear inside each sampling interval in a logarithmic scale with base 2. Let t_1 denote the mean of the sampling interval and t denote the time from this interval. Then we have for the specific current density i_r

$$i_r(t) = \frac{\mathrm{d}q}{\mathrm{d}t} = \frac{q\big(\sqrt{2}t_1\big) - q\big(\frac{t_1}{\sqrt{2}}\big)}{t\ln 2}\,. \quad (14)$$

This equation is valid for each point nt_1. Let us denote the numerator of (14) as $\Delta q(n)$. Then the Fourier transform of $i_r(t)$ will be a sum of integrals from all of sampling intervals

$$\varepsilon^*(\omega) = \frac{1}{\ln 2}\sum_{p=-\infty}^{\infty}\Delta q(n)\int_{\frac{nt_1}{\sqrt{2}}}^{n\sqrt{2}t_1}\frac{1}{t}e^{-j\omega t}\mathrm{d}t\,, \quad (15)$$

where $n = 2^p$. After dividing (15) to the real and imaginary parts we have

$$\varepsilon^*(\omega) = \sum_{p=-\infty}^{\infty} \Delta q(n)[x(n) - jy(n)],$$

$$x(n) = \frac{1}{\ln 2}\int_{\frac{nt_1}{\sqrt{2}}}^{n\sqrt{2}t_1} \frac{\cos\omega t}{t}\mathrm{d}t, \quad y(n) = \frac{1}{\ln 2}\int_{\frac{nt_1}{\sqrt{2}}}^{n\sqrt{2}t_1} \frac{\sin\omega t}{t}\mathrm{d}t. \qquad (16)$$

The integrals in terms for $x(n)$ and $y(n)$ were evaluated for values $n\omega t_1$ which are powers of 2. The table of values $x(n)$ and $y(n)$ can be found in [4]. According to published results, satisfactory accuracy was reached by using 5 coefficients from the sum (16).

2.4 The Adamec approximation

The method developed by Adamec [1] is similar to the Hyde approximation. Here a linear dependence of conductivity is supposed inside each sampling interval in a logarithmic scale. The method resulted into two sums

$$\varepsilon'(\omega) = \frac{t_i}{\varepsilon_0}\sum_{p=-\infty}^{\infty} \gamma_a\Big(\frac{rt_i}{\sqrt{2}}\Big)a(r),$$

$$\varepsilon''(\omega) = \frac{t_i}{\varepsilon_0}\sum_{p=-\infty}^{\infty} \gamma_a\Big(\frac{rt_i}{\sqrt{2}}\Big)b(r), \qquad (17)$$

where $r = 2^p$ $(-\infty < p < \infty)$, $t_i = 1/\omega$. Good accuracy was declared by using 9 elements from series (17). The table of coefficients $a(r)$ and $b(r)$ can be found in [1].

2.5 Fitting an absorption conductivity by a linear combination of exponentials

The method of resolving absorption conductivity into its components relates to the theory of distribution of relaxation times. According to this theory there is a continuous distribution of potential barriers in a dielectric. As the relaxation times are proportional to the potential barriers magnitude, they also have their own distribution. It should be mentioned that some serious objections to the acceptance of this theory exist [5]. In spite of this, fitting of experimental data by a sum of exponentials is a commonly used method preferably in the field of diagnostics and also in modelling the interfacial polarisation of a multi-layer dielectric. Calculation of the Fourier transform in this case is easy. Suppose that the absorption conductivity is given as

$$\gamma_a = \sum_{i=1}^{n} \gamma_i \exp\Big(-\frac{t}{\tau_i}\Big). \qquad (18)$$

After introducing new parameters $\Delta\varepsilon_i = \frac{\gamma_i\tau_i}{\varepsilon_0}$ and performing the Fourier transform we have

$$\varepsilon^*(\omega) = \varepsilon_\infty + \sum_{i=1}^{n} \frac{\Delta\varepsilon_i}{1+\omega^2\tau_i^2} - j\sum_{i=1}^{n} \frac{\Delta\varepsilon_i\omega\tau_i}{1+\omega^2\tau_i^2}. \qquad (19)$$

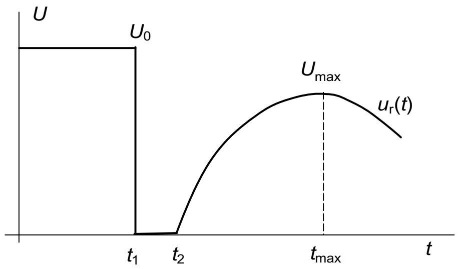

Fig. 1. Time dependence of the voltage during the recovery voltage test

To find parameters γ_i, τ_i some static optimisation methods are used. The optimisation begins with fitting the measured data by one exponential. The number of exponentials is incremented by 1 while all parameters γ_i, τ_i are positive [6]. Another approach to the optimisation is based on generation of logarithmic spaced relaxation times [7]. Usually two or three relaxation times per decade are sufficient to fit the data. The coefficients γ_i are determined by means of the least squares method. All relaxation times for negative coefficients γ_i are then eliminated. This procedure is repeated until all coefficients are positive.

3 CALCULATION OF THE COMPLEX PERMITTIVITY FROM THE TIME DOMAIN VOLTAGE MEASUREMENTS

3.1 Principles of the recovery voltage method

The converting procedures described above are based on the absorption current measurement. The absorption current is in many cases very small and sensitive to noise. To eliminate this disadvantage an alternative method based on voltage measurement was introduced. It is called the recovery voltage method. During the recovery voltage measurement a constant voltage U_0 (electric field E_0) is applied to the test object for $0 \le t < t_1$. In the time period $t_1 \le t < t_2$ the object is short-circuited and then it is left in open-circuit condition. The voltage on the test object is measured for $t_2 \le t$ with a high input impedance voltmeter. Time diagram of the process is shown in Fig. 1.

In connection with the recovery voltage measurements a derived quantity called "polarisation spectrum" was introduced. It was determined as a dependence of the recovery voltage maxima $U_{\max}$ on the corresponding time $t_{\max}$ for changing t_1. A professional instrument named Recovery Voltage Meter was developed and produced for testing recovery voltage on power equipment. It was mainly used for finding the moisture content in the power transformers insulation [8]. It was found later that the polarisation spectrum cannot be considered as the only criterion of the moisture content [7, 9].

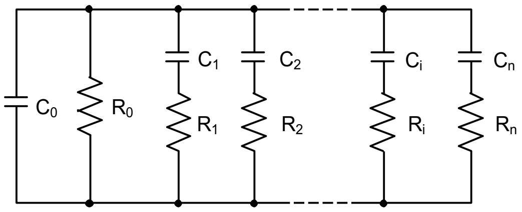

Fig. 2. Equivalent circuit for modelling the recovery voltage

In the last few years an empirical approach to the recovery voltage test was replaced by attempts for exact solution of the transient phenomenon which appears in the dielectric during the test [10, 11, 12]. The problem of the recovery voltage data conversion from the time domain into the frequency domain was also partially solved. The data conversion can be accomplished in two ways:

1. By modelling the process with help of an equivalent circuit.
2. By solving equation (1) for $E(t)$ in time interval $t_2 \le t$.

3.2 Equivalent circuit for modelling the recovery voltage data

The equivalent circuit used for modelling is in Fig. 2. Here C_i, R_i are individual elements of the circuit, n is the number of elements, C_0 is the capacitance corresponding to the optical permittivity and R_0 is the resistance corresponding to the steady state conductivity.

Let $u_i(t)$ $i = 1, 2, \dots, n$ be voltages across the capacitances C_i and $u_r(t)$ be the voltage across the capacitance C_0. Then the next set of differential equations is valid for $t_2 < t$

$$\begin{aligned} \frac{\mathrm{d}u_i}{\mathrm{d}t} &= \frac{1}{R_i C_i}(u_r - u_i), \quad i = 1, 2, \dots, n, \\ \frac{\mathrm{d}u_r}{\mathrm{d}t} &= \frac{1}{C_0}\Big[-\frac{u_r}{R_0} - \sum_{i=1}^{n} \frac{u_r - u_i}{R_i}\Big]. \end{aligned} \tag{20}$$

The initial value of u_i (assigned as U_i) depend on the charging and discharging period

$$U_i = U_0\Big(1 - \exp\big(-\frac{t_1}{R_i C_i}\big)\Big)\exp\big(-\frac{t_2 - t_1}{R_i C_i}\big). \tag{21}$$

The system of equations (20) can be solved by using the Laplace transform. Denoting the Laplace transform of $u_r(t)$ by $u_r(p)$ we have

$$u_r(p)\big(\frac{1}{R_0} + pC_0\big) = \sum_{i=1}^{n}\big(U_i - u_r(p)\big)\frac{pC_i}{1 + p\tau_i}, \tag{22}$$

where $\tau_i = R_i C_i$.
Equation (22) can be written in the form

$$u_r(p) = \frac{NUM(p)}{DEN(p)}. \tag{23}$$

The numerator $NUM(p)$ and denominator $DEN(p)$ are given by

$$\begin{aligned} NUM(p) &= R_0 \sum_{i=0}^{n} C_i U_i \prod_{\substack{j=1\\ j\neq i}}^{n}(1 + p\tau_i), \\ DEN(p) &= \prod_{i=0}^{n}(1 + p\tau_i) + pR_0 \sum_{i=0}^{n} C_i \prod_{\substack{j=1\\ j\neq i}}^{n}(1 + p\tau_i). \end{aligned} \tag{24}$$

From (24) it can be seen that the degree of polynomial $NUM(p)$ is less than the degree of polynomial $DEN(p)$. In this way we can compute the inverse Laplace transform of $u_r(p)$ from the rational function of (23) by standard procedure of partial fraction expansion. In practice the values of C_0 and R_0 are known from some additional measurements. As the values of $u_r(t)$ are measured during the recovery voltage test, the unknown parameters in equation (23) are only the pairs (R_i, C_i).

For finding a set of unknown parameters optimisation methods are preferably used. A problem here is to find a good starting guess of parameters. If the starting guess is poor, the calculation can be sensitive to round-off errors and the method does not converge. According to [13] a good approximation of the recovery voltage data was found already for a set with two pairs (R_i, C_i). A method similar to fitting the absorption conductivity by a linear combination of exponentials modified for recovery voltage tests was also published [14].

3.3 Calculation of the recovery voltage transient by using the Maxwell equation

For calculation of the recovery voltage transient, the Maxwell equation for current density is modified to the form

$$i(t) = \gamma_0 E(t) + \varepsilon_0 \varepsilon_r \frac{\mathrm{d}E(t)}{\mathrm{d}t} + \varepsilon_0 \frac{\mathrm{d}}{\mathrm{d}t}\int_0^t h(t - \lambda)E(\lambda)\mathrm{d}\lambda. \tag{25}$$

Permittivity ε_r of the polarisations faster than the polarisation treated in the recovery voltage test is taken into account instead of the value of optical permittivity. The integral on the right side of equation (25) can be partially solved for intervals from 0 to t_1 and t_1 to t_2:

$$\begin{aligned} i(t) = \gamma_0 E(t) + \varepsilon_0 \varepsilon_r \frac{\mathrm{d}E(t)}{\mathrm{d}t} + \varepsilon_0\Big[\frac{\mathrm{d}}{\mathrm{d}t}\int_{t_2}^{t} h(t - \lambda)E(\lambda)\mathrm{d}\lambda \\ + E_0\big(h(t) - h(t - t_1)\big)\Big]. \end{aligned} \tag{26}$$

The current density on the left side of equation (26) equals to zero as the measuring circuit is opened. The equation was numerically solved for known values of ε_r

and γ_0 supposing that $h(t)$ has a special form (so-called universal response) with four unknown parameters [5, 15]. From the known values of $h(t)$ the complex permittivity can be easily computed using relationships (4) and (6).

According to [15] another method was also developed to calculate the dielectric response from recovery voltage data. This method expresses the dielectric response and the recovery voltage as a series of basis function. A very simple choice of basis function is the exponential function. After applying the basis functions in equation (26), a set of linear equations for parameters of the basis functions can be formatted. This is also difficult to solve as the matrix is poorly conditioned.

4 A NEW APPROACH TO THE CONVERSION OF RECOVERY VOLTAGE DATA INTO THE FREQUENCY DOMAIN AND ITS EXPERIMENTAL VERIFICATION

Let us suppose that the value of impulse function for $t = t_1$ equals zero (the dielectric is entirely charged). Then the value $h(t)$ can be neglected comparing with $h(t-t_1)$. For the last term in equation (26) we can write: $h(t) - h(t-t_1) \approx -h(t-t_1)$. As the time interval $t_2 - t_1$ is very short, we can also suppose that $h(t_1) = h(t_2)$. Under these assumptions it is possible to shift the origin of the time axis from zero to t_2. In practice, the specific values γ_0, ε_r of the measured object are not known, so we use values of capacitance and conductance instead of them. Taking these notices into account we can rewrite equation (26) as follows

$$0 = Gu_r(t) + C_0 \frac{\mathrm{d}u_r(t)}{\mathrm{d}t} + C_g \Big[\frac{\mathrm{d}}{\mathrm{d}t} \int_0^t h(t-\lambda) u_r(\lambda) \mathrm{d}\lambda - U_0 h(t) \Big] , \quad (27)$$

where C_0 is the capacitance corresponding to the fast polarisations, G is the conductance corresponding to the steady state conductivity, C_g is geometric or vacuum capacitance. Other symbols are of the same meaning as in the preceding part. After performing the Fourier transform of equation (27) we have

$$C_g h^*(\omega) = \frac{u_r^*(\omega)(G + j\omega C_0)}{U_0 - j\omega u_r^*(\omega)} , \quad (28)$$

where $u_r^*(\omega)$ is the Fourier transform of recovery voltage and $h^*(\omega)$ is the dielectric susceptibility. Conversion of recovery voltage data according to equation (28) is very simple. Complicated optimisation methods and iterative procedures need not be used. The only operation which must be done is the Fourier transform of the time domain recovery voltage data.

In experimental part, results achieved according to the new approach described above were compared with results of modelling the recovery voltage data by means of the equivalent circuit shown in Fig. 2 and also with results of conversion of the absorption current data. The three computing procedures were applied to the data measured on simple circuits consisting of discrete components as well as on real dielectrics (PVC cables).

A charging voltage of 100 V was applied to the sample for a period of 5000 s and the absorption current was measured simultaneously. Next, the sample was short-circuited for 0.1 s by means of a computer controlled relay and then connected to a high input impedance voltmeter. The recovery voltage was measured in a period of 5000 s. For measurements of both the absorption current and recovery voltage a Keithley 617 electrometer was used with a built in source of charging voltage. The electrometer was controlled by GP-IB interface.

The measured values of absorption current were fitted by a sum of exponentials and a constant term (steady-state current). To find the parameters of exponentials, Nelder-Mead simplex algorithm was used. The optimisation began with fitting the measured data by one exponential. The number of exponentials was incremented by one while all parameters were positive. The sum of exponentials was then converted into the frequency domain by means of the Fourier transform.

The recovery voltage values were processed first by using the equivalent circuit shown in Fig. 2. The procedure was as follows:

1. A starting guess of R_1, C_1 was computed from the peak value of the recovery voltage and the time at which the peak was reached.
2. The inverse Laplace transform of (23) was performed by means of partial-fraction expansion.
3. The sum of squares of the difference between the measured data and the inverse Laplace transform was minimised by changing the starting guess according to Nelder-Mead simplex algorithm.
4. The next two pairs of R_i, C_i were estimated so that $C_2 = C_3 = C_1$, $R_2 = 0.1\,R_1$, $R_3 = 100\,R_1$.

Steps 2, 3 and 4 were repeated while the difference between the measured and calculated values descended significantly. After finishing this computation, data were converted into the frequency domain using equation (19). The value of C_0 needed for calculation was measured by the HIOKI Z HiTESTER 3531 at 1 kHz. The insulation resistance R_0 was calculated from the steady-state value of absorption current.

The recovery voltage values were also processed by equation (28). Here the Fourier transform was not performed in a discrete form like in equation (7) but in a similar way like the transform of absorption current — the recovery voltage was fitted by a sum of exponentials. The influence of the number of exponentials used for fitting is illustrated in Fig. 3. The data were measured on a model circuit consisting of capacitance C_0, resistance R_0 and three series RC elements connected in parallel with C_0 and R_0. It can be seen that an increasing number of

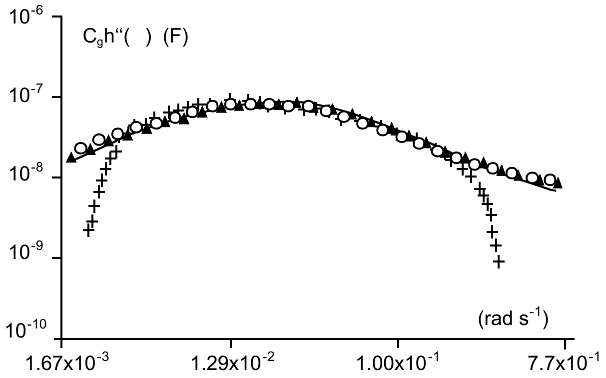

Fig. 3. The influence of the number of exponentials used for fitting the recovery voltage data on the Fourier transform results. Legend: solid line — calculated from the absorption current, $+$, ▲, ○ — calculated from recovery voltage fitting with 5, 10 and 15 exponentials respectively.

exponentials does not always lead to more accurate results. In our case the results for 10 and 15 exponentials are equal.

Typical results of data conversion from the time domain into the frequency domain are shown in Figs. 4 and 5. The data were measured on a model circuit (Fig. 4) and PVC cable insulation (Fig. 5). As it is seen from Fig. 4, there is good agreement between the imaginary part of $C_g h^*(\omega)$ calculated from the absorption current (solid line), calculated from the equivalent circuit with five RC elements (transparent circles) and the one calculated according to equation (28) (filled circles). The agreement is not very good for results of measurements on PVC cable insulation, especially near the low frequency region. Possible sources of errors are discussed in conclusion of this paper.

5 CONCLUSION

This paper presents a review of methods used for conversion of the dielectric data from the time domain into the frequency domain. The methods come out from measurements of the absorption current or recovery voltage. A new method is also presented, based on the Fourier transform of recovery voltage data. Two methods from the older ones were chosen along with the new method for processing data obtained experimentally on a model circuit and also on a real dielectric. The two methods based on recovery voltage measurements provide practically identical results. On the other hand, the results derived by the methods based on recovery voltage measurements differ from the results of the absorption current method especially at the ends of the frequency region. These differences can be probably caused by the drift of the small current measuring unit during the long-time process of measurement. Specimen history and some additional effects (*eg* presence of a space charge, a short discharging time) can also influence the results.

In general, it can be stated that the methods based on the measurement of the recovery voltage are suitable for finding out the dielectric parameters. The only disadvantage is that they still require a knowledge about the system conductivity or resistance. The method based on modelling the dielectric by means of an equivalent circuit seems to be more flexible as it allows to change the charging and discharging period of the recovery voltage test. The analysis of recovery voltage data by means of the newly developed method is relative easy and does not depend on the starting guess like other optimisation methods. It is also faster comparing with the method based on the equivalent circuit. It is suitable for practical use in dielectric and insulation diagnostics. We suppose that it will be possible to modify this method for changeable charging and discharging times.

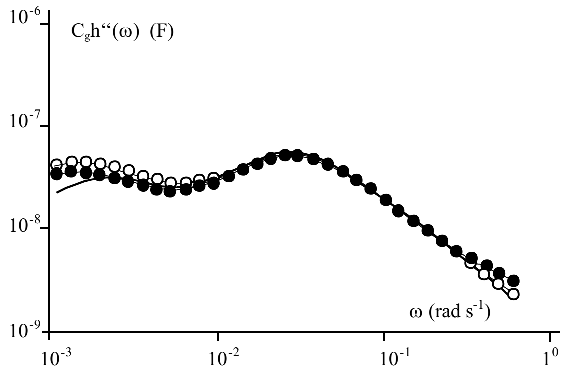

Fig. 4. Comparison of the results of conversion from the time domain into the frequency domain derived by different methods for a model circuit. Legend: solid line — calculated from the absorption current, ○ — calculated from the equivalent circuit, • — calculated according to equation (28).

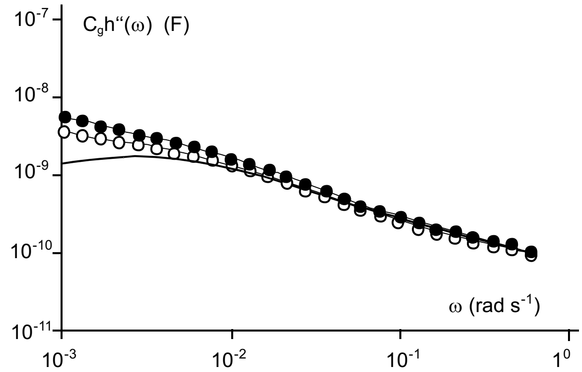

Fig. 5. Comparison of the results of conversion from the time domain into the frequency domain derived by different methods for a PVC cable insulation. Legend: solid line — calculated from the absorption current, ○ — calculated from the equivalent circuit, • — calculated according to equation (28).

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Vladimír Ďurman (Ing, PhD), born in Nov Mesto nad Váhom, Slovakia, in 1946, graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in electrotechnology branch in 1968, and received the CSc (PhD) degree in Electrotechnology at the same university, in 1979. At present he is a research worker at the Department of Electrotechnology, Faculty of Electrical Engineering and Information Technology. He is engaged in research of dielectrics and dielectric properties of materials.

Martin Wiesner. Biography not supplied.

Jaroslav Lelák (Doc, Ing, PhD) was born in Piešťany in 1951. He graduated from the Slovak University of Technology, Faculty of Electrical Engineering in 1974. He received PhD degree from the Moscow Institute of Power Engineering in 1985. In 1996 he was appointed Associate Professor at the Department of Electrotechnology. His main interests are degradation processes in insulation systems, durability, and reliability of electrical power systems and prophylactic measurements on high voltage equipment. He reads lectures in Optical and metallic cables, Technology of electrical machines and High voltage technique.

Ondrej Olach (Doc, Ing, PhD), born in Tekovské Lužany, Slovakia, in 1943, graduated from the Faculty of Electrical Engineering, Slovak Technical University, Bratislava, at Solid State Physics branch in 1967, and received the CSc (PhD) degree in Electrotechnology at the same university, in 1978. Since 1989 he has been working as Associate Professor at the Department of Electrotechnology, Faculty of Electrical Engineering and Information Technology. He is the Head of Department of Electrotechnology. His research activity has been focused on the dielectric properties of materials and electrical components.